

FREQUENCY-SELECTIVE SILENCING DEVICE FOR DIGITAL FILTERING OF AUDIBLE MEDICAL ALARM SOUNDS TO ENHANCE ICU PATIENT RECOVERY

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ABSTRACT

Free-field auditory medical alarms, although widely present in intensive care units, have created many hazards for both patients and clinicians in this environment. The harsh characteristics of the alarm noise profile combined with the frequency at which they sound throughout the ICU have created discomfort for the patients and contribute to psychological problems, such as PTSD and delirium. This frequency-selective silencing device seeks to attenuate these problems by removing the alarm sounds from the patient perspective. Patients do not need to hear these alarms as the alarms primarily serve to alert clinicians; therefore, this device, using a Raspberry Pi and digital filters, removes the alarm sounds present in the environment while transmitting other sounds to the patient without distortion. This allows for patients to hear everything occurring around them and to communicate effectively without experiencing the negative consequences of audible alarms.

1. INTRODUCTION

Significant issues plaguing successful patient recovery in Intensive Care Units (ICUs) are the frequent occurrence of clinical alarms and the harsh, shrill noises that generally characterize these sounds. Alarms sound frequently to alert clinicians of physiologic aberrancy that exceeds a threshold - yet many alarms have low positive predictive value, meaning that there are high rates of false positives indicated by alarms [1]. As stated by Edworthy, multiparameter auditory warnings can be combined to create varying degrees of urgency [2]. Although the utilization of these results has proven useful to alert clinicians of possible danger, the potential negative consequences from the piercing alarm sounds were not considered from the patient perspective. These alarms have been responsible for numerous negative consequences for both patients and physicians in the ICU. While clinicians can suffer from alarm fatigue and desensitization, the patient-specific consequences are of the

utmost concern, as patients commonly experience Post Traumatic Stress Disorder (PTSD) anchored to critical illness and delirium after a stay in the ICU, as assessed by the Clinician-Administered PTSD Scale for DSM-5 (CAPS-5) and the Confusion Assessment Method for the ICU (CAM-ICU), respectively [4]. According to Wade, 88% of the ICU patients interviewed experienced hallucinatory/delusional intrusive memories related to ICU care for up to 8 months after hospital discharge [3]. These memories were not factual but rather were fabricated memories or ideas that may have been based on or influenced by experiences in the ICU. Additionally, Pandharipande found that prior to ICU admission, only 6% of patients showed evidence of mild-to-moderate cognitive impairment [4]. After discharge from the ICU, this number increased to 25% of patients.

While the underlying causes of these disorders are not determined, the frequent, loud noises produced by clinical alarms often wake patients in the middle of the night, disturb their sleep patterns, and sound for extended lengths of time with no healthcare provider explanation to the patient regarding the reason behind the alarm. In work from Lutter, 67.2% of the alarms from three different machines in the ICU were false positives [5]. These situations can be incredibly disorienting for patients and could potentially contribute to psychological problems after discharge from the ICU. Furthermore, the fact that false alarms are so prevalent further justifies the fact that they cause an unnecessary amount of noise exposure in the ICU environment. If the alarm sounds are not detected by the patient, the likelihood of developing these psychological disorders may be reduced. It is critical to understand that patients do *not* need to hear alarms in these environments; the information conveyed by medical equipment is to signal to physicians and nurses to act, but patients themselves do not need to hear the harsh and shrill tones that occur with free-field audible medical alarms.

Future projects can completely avoid free-field alarms by transmitting signals directly to in-ear devices worn by physicians and nurses that correspond to the patients to whom they are specifically attending. As a step-wise approach, this initial patient-focused device can act as an

interim solution and help alleviate the problems experienced by the patients while the more involved physician-focused device is developed.

This approach expands on the concept of avoiding unnecessary alarms in already busy and noisy hospital settings. This is accomplished by the creation of a wearable frequency-selective silencing device. The solution to this problem silences the frequencies corresponding to the alarm noises (primarily patient monitor red/crisis alarm) and will allow the passage of all normal sounds (speech and other environmental stimuli), while maintaining their quality to reduce the likelihood of delirium.

2. DEVICE DESIGN NEEDS

The wearable technology must be user-friendly and comfortable to allow for continuous patient wear, especially while the patient is asleep. Additionally, the device may reduce the occurrence of PTSD and delirium in the ICU by blocking alarm sounds while allowing the passage of all other environmental noise, such as speech and TV sounds. It is important to note that overstimulation of the auditory sense as well as a complete lack of stimulation of the auditory sense can contribute to PTSD and delirium, which is why noise-cancelling headphones and/or simple earplugs that dampen all environmental noise entirely are *not* the desired solution [4].

Keeping this in mind, the device shall not muffle or distort any normal environmental sounds as this could lead to negative consequences for the patient. This also mandates that the device process environmental noise in real-time because a noticeable delay could also contribute to psychological distress for the patient. The device should also be equipped with a detection method so that the filtering system is only activated when an alarm noise is present in the environment. By including this feature, the likelihood of unnecessarily distorting speech can be reduced and ICU-induced PTSD can further be avoided.

3. DIGITAL SIGNAL PROCESSING

To remove the alarm sound, MATLAB (MathWorks, Natick MA) Digital Signal Processing was utilized to initially implement and test our digital filters. This experimental process required multiple iterations to determine the filter metrics that successfully removed the alarm sounds. A spectral analysis was performed on a single alarm sound to obtain its frequency components. Then, an Infinite Impulse Response (IIR) Elliptic bandstop filter was created to block the frequency that specifically dominated in the spectral analysis. The width of the stopband had to be optimized so that the alarm component was completely blocked yet the effect on environmental noise was minimized. The sound file

was then filtered by the newly created bandstop filter, and another spectral analysis was performed to determine the next most prominent frequency component. This led to the creation of filters targeting the common red/patient crisis alarm with the most important ones focused at 960 Hz, 1920 Hz, 2880 Hz, and 3840 Hz.

The dynamic digital filter was then generated in Simulink (MathWorks, Natick MA) using the filter specifications determined in MATLAB. The design is two-fold in that it contains both a detector and a series of filters. The detector continuously processes all incoming environmental sounds and determines the power present in the unfiltered environmental noise as compared to the power present in the filtered version. If this difference exceeds a predetermined threshold, this serves to indicate that an alarm is present in the environment. If the alarm sound is detected, the detector switches on the digital filter, and the filtered version of the noise is passed to the patient. This switching mechanism is critical to the design as it ensures that unnecessary processing and potential distortion will not occur for the patient if no alarms are sounding in the environment. Implementing the detector will further confirm that the patient will not experience ICU-induced psychological problems.

The procedure involved obtaining several recordings of the alarm sound without any background noise. These recordings were used to create and design various filters that eliminated the prevalent frequencies, which comprise the shrill and harsh sound of the alarm. Then, the original alarm sound wave file (.wav) was processed using the created filter and it was shown that the entirety of the alarm was silenced.

Furthermore, another set of recordings were obtained, and these contained the alarm sound with various environmental conditions (television playing in the background, doctors and nurses speaking, presence of pulse oximetry). These recordings were processed using the same filter mentioned above to show that the sound waves associated with the alarm were entirely removed, while maintaining the integrity and ensuring the passage of all other sounds.

4. DEVICE COMPONENTS

The hardware portion of this device continuously completes the digital filtering task during the device's operation. To do this, the Simulink code for the detector and filter has been uploaded onto a Raspberry Pi (Raspberry Pi Foundation, Cambridge UK) to allow for alarm filtration. A microphone connected to the Raspberry Pi obtains and passes the environmental sound to the digital detector. As previously mentioned, the Raspberry Pi digitally filters the predetermined alarm sound frequencies while letting the other environmental sound frequencies pass. The filtered signal is then transmitted as an output to the user through passive noise cancelling earbuds. It is important that these earbuds are noise cancelling so that the alarm sound that is present in the environment does not pass through traditional headphones and leak into the sound that is heard by the patient. Using



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noise cancelling headphones ensures that only the filtered alarm sound is passed to the patient and that the goal of the design is accomplished [Figure 1].



Figure 1: Frequency-Selective Silencing Device

5. PROOF OF CONCEPT

5.1. Experimental design and testing

The testing methods are two-fold, subjective and objective – the subjective testing utilizes human participants to determine if speech intelligibility is maintained with alarm filtering, as outlined in the device design needs statement.

5.1.1. Subjective testing background

We utilized the seminal approach for speech intelligibility testing, as outlined by Lehist *et al* [6]. Intelligibility is defined as a property of speech communication involving meaning. We utilized the consonant-nucleus-consonant (CNC) paradigm for subjective speech intelligibility testing. The CNC paradigm presents monosyllabic words to the participants and the experimenter scores each word based on the number of phonemes repeated correctly. A phoneme has little lexical meaning as an unclassified speech event – phonemes are signals, not symbols. The CNC word lists are phonemically and phonetically balanced. As the term “phonetics” is normally used in American linguistics, it concerns the physiological and acoustical properties of speech [6]. The ten CNC lists are composed of 50 words each, representing a selection of 500 words from the total of 1,263 which are refined from the Thorndike and Lorge volume after phonetic/phonemic balancing [7]. As an example, participants would be exposed to a monosyllable such as “goose.” The word “goose,” as all monosyllables in the CNC sets, contains three phonemes. The first phoneme, the consonant is a hard “g” (say ‘guh’). The second phoneme, the vowel or nucleus is a prolonged “o” (say ‘ooo’). And, the third phoneme, the second consonant, has a hissing “s” sound. These phonemes were individually scored for each word. If the participant uttered “goose,” the entire word is marked as

correct. If the participant uttered “goo” for the word “goose,” the resultant score would be ~66%, as the first and second phonemes were correct.

5.1.2. Subjective testing methods

Twenty-four (24) participants ranging 18-22 years of age participated in the subjective testing paradigm. After consent and ensuring normal or corrected to normal hearing, the participants were brought into a simulated ICU setting where they laid down on a bed with a patient monitor alarm stimulus approximately 6 feet above their heads at a 45-degree angle from their head position, similar to an ICU patient monitor location. The speech stimulus was positioned 4 feet above their head and directed towards the unilateral ear as the alarm stimulus. The speech stimulus was positioned as if another person was standing at their bedside and speaking to them. To ensure there was not confounding from the alarm stimulus simply secondary to volume, and based on recently completed work on the negative signal-to-noise ratio in the Schlesinger lab, the alarm stimulus was delivered at 70 dB and the speech stimulus was delivered at 77-79 dB as verified with an Amprobe SM-10 Class II sound level meter (Amprobe, Lynbrook, NY). The participants wore Bose QuietComfort 20i earbuds (Bose, Framingham, MA) connected to the device for stimuli exposure. To prevent the subjects from “searching” for the alarm sound in the background noise, they were not told that the device is intended to filter alarm noises but simply asked if they heard alarms throughout their time during the testing and to repeat the CNC word back to the experimenter. The participants were exposed to two randomly selected sets of 50 CNC words. One set would have alarm filtering, and the other set would have no alarm filtering. The sets of 50 words were purposely different to avoid a learning effect. The study lasted approximately 15 minutes per participant with breaks offered between CNC word sets [Figure 2].

5.1.3. Objective testing methods

Objectively proving that the device accomplished the project aims, an experiment was performed to demonstrate that the frequency components specific to the alarms were missing from the filtered sound. In the initial stages of the project, a Fast Fourier Transform (FFT) was performed using MATLAB and Simulink on the unfiltered alarm sound sample and the filtered alarm to compare the magnitudes of the frequency components present between the two sounds [Figures 3a, 3b, 4a and 4b].

5.2. Results

The subjective CNC testing yielded clinically and statistically significant improvement with alarm filtering. The phoneme score improved from 42.54% (95% CI: 38.96, 46.12) to 56.71% (95% CI: 53.32, 60.10) correct with alarm filtering ($p < 0.001$). The word score improved from 18.42% (95% CI: 14.62, 22.22) to 27.42% (95% CI: 23.17, 31.67) correct with alarm filtering ($p < 0.01$) [Figure 2]. Additionally, besides these data, the participants endorsed a high-stress state during alarm exposure.

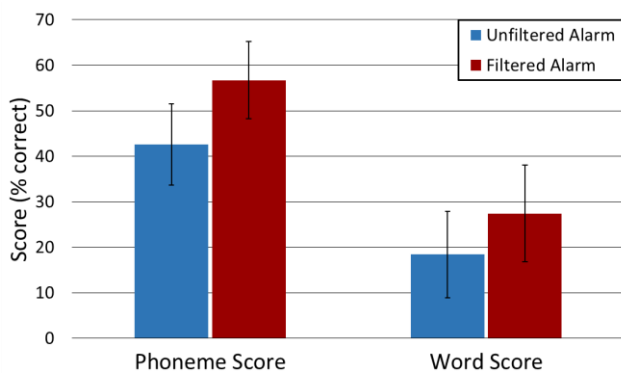


Figure 2: Improved phoneme and word score with alarm filtering (error bars signify standard deviation)

In the objective testing using MATLAB, the series of bandstop filters created on MATLAB dampened the magnitudes of the frequencies present in the alarm on the order of 10^3 , as seen in Figures 3a and 3b (note the Y-axis values).

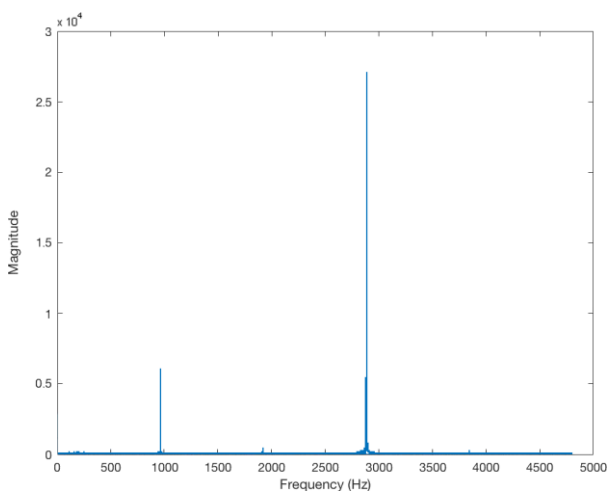


Figure 3a: FFT of a single unfiltered alarm (a) and the same alarm filtered by a series of bandstop filters (b)

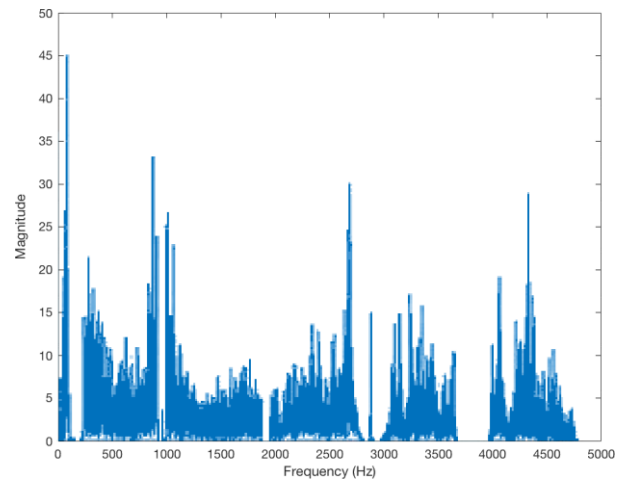


Figure 3b: FFT of a single unfiltered alarm (a) and the same alarm filtered by a series of bandstop filters (b)

Once the filtering on MATLAB proved successful, Simulink (MathWorks) was used to compile the software and deploy the data onto a Raspberry Pi device. By utilizing a file (.wav) with both the alarm sound and environmental noise present, it was proven that the Simulink software could successfully filter the alarm frequencies as shown in Figures 4a and 4b (note the Y-axis values).

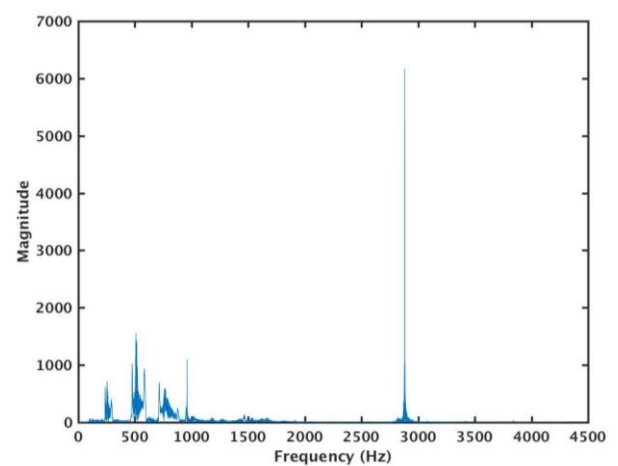


Figure 4a: Fast Fourier Transform of unfiltered real-time audio output containing speech and alarm sounds

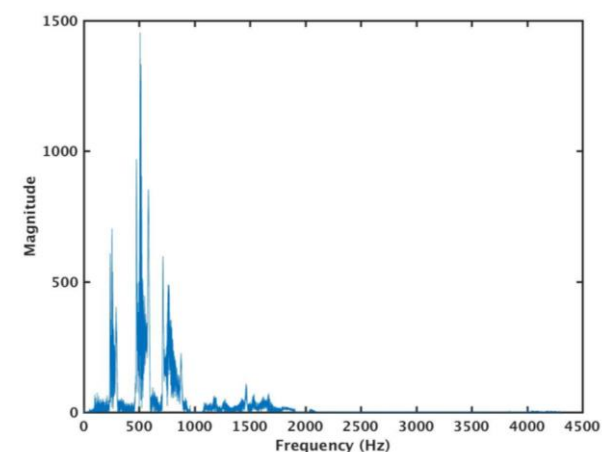


Figure 4b: Fast Fourier Transform of real-time audio output with speech and filtered alarm sounds

5.3. Expected patient benefit

Following the successful implementation of the digital signal processing onto the Raspberry Pi hardware, it is expected that the Raspberry Pi will output an audio signal that will contain the original input audio signal without the alarm-sound frequencies. The Raspberry Pi should be able to do real time filtering of audio signals input through the microphone attachment to the Raspberry Pi. Using the switch, the user should be able to hear an output signal of the filtered environmental noise only when the alarm sound is present. Furthermore, the patient should be able to hear an output signal of the original environmental noise when the alarm sound is not present; therefore, not experiencing any distortion of the sound and the only change being the elimination of the alarm frequencies.

5.4. Expected clinician benefit

While this device was designed for the patient, the future directions indicate developments for the clinician. However, with this patient-centered device, the benefits are manifold. Besides filtering out unnecessary alarms for patients, speech intelligibility will be improved between patients and the healthcare team. This is imperative during patient and family centered rounds in the ICU where complex care plans are discussed and the patient must fully understand the risks and benefits of all treatment options before giving consent. Additionally, improving patient satisfaction and minimizing disruptions in the healthcare setting by attenuating the alarm exposure for the patient may further enhance the patient-clinician relationship. In the face of decreased deleterious neuropsychological outcomes for patients, there may be decreased length-of-stay, and improved healthcare economics.

6. LIMITATIONS AND FUTURE DIRECTIONS

This device relies on the use of noise-cancelling headphones to transmit the filtered sound to the patient. Future design will incorporate a wireless, in-ear device that can perform all the necessary filtering functions and transmission of the filtered sound in the device itself. With respect to the overarching problem of audible medical alarms, this device serves as an interim solution that may solve the patient problems of PTSD, delirium and general patient discomfort. However, the physician-related problems still remain. Thus, as previously discussed, a second in-ear device is in the process of being developed that transmits alarms and patient information directly from the patient monitors and equipment in the patient room to the physician or nurse at the optimal signal-to-noise ratio. This device would suppress the need to have audible free-field medical alarms. The patient specific device described herein would remain necessary in the likely slow transition to, or absence of complete global adoption of healthcare provider in-ear monitoring devices.

7. CONCLUSION

Audible medical alarms are the cause of myriad hazards in hospital and ICU settings. Their shrill acoustic features and the frequency at which they alarm (both in sheer number and frequency spectrum) are responsible for many negative consequences, especially for patients. Patients can experience PTSD and delirium secondary to sleep disturbance from alarms and healthcare providers' divided and diminished attentional resources allocated to alarms. This frequency-selective silencing device was created to alleviate these problems and create a more comfortable environment for the patients during their length of stay in the ICU. This device has been demonstrated to successfully remove alarm sounds while avoiding audible distortion of speech and other environmental noise, and should it be widely implemented in hospital setting, it will prevent patients from hearing the disturbing and potentially harmful sounds of free-field medical alarms and may improve patient safety.

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